

Hadron Spectroscopy in the Unquenched Quark Model*

H. GARCÍA-TECOCOATZI^{1,2}, R. BIJKER¹, J. FERRETTI³, E. SANTOPINTO²

¹*Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, AP 70-543, 04510 México DF, México*

²*INFN Sezione di Genova and Dipartimento di Fisica, Università di Genova, via Dodecaneso 33, I-16146 Genova, Italy*

³*Dipartimento di Fisica and INFN, Università di Roma "Sapienza", Piazzale A. Moro 5, I-00185 Roma, Italy*

E-mail: hugo.garcia@nucleares.unam.mx

(Received September, 2015)

We present the last applications of the unquenched quark model (UQM) to the description of flavour asymmetry and strangeness in the proton when baryon-meson components are included. In the meson sector, the UQM is used to calculate the charmonium and bottomonium spectra with self-energy corrections due to the coupling to the meson-meson continuum.

1. Introduction

The behavior of observables such as the spectrum and the magnetic moments of hadrons are well reproduced by the constituent quark model (CQM) [1–10], even if it neglects quark-antiquark pair-creation (or continuum-coupling) effects. The unquenching of the quark model for hadrons is a way to take these components into account.

The unquenching of CQM was initially done by Törnqvist and collaborators, who used an unitarized quark model [13, 14], while Van Beveren and Rupp used a t-matrix approach [11, 12]. These techniques were applied to the study of scalar meson nonet (a_0 , f_0 , etc.) of Ref. [12, 15] in which the loop contributions are given by the hadronic intermediate states that each meson can access. It is via these hadronic loops that the bare states become “dressed” and the hadronic loop contributions totally dominate the dynamics of the process. A similar approach was developed by Boglione and Pennington in Ref. [16], in which they investigated the dynamical generation of the scalar mesons by initially inserting only one “bare seed”. On the other hand, Isgur and coworkers in Ref. [17] demonstrated that the effects of the $q\bar{q}$ sea pairs in meson spectroscopy is simply a renormalization of the meson string tension. The strangeness content of the nucleon and electromagnetic form factors were also investigated, see refs. [18, 19], whereas Capstick and Morel in Ref. [20] analyzed baryon meson loop effects on the spectrum of nonstrange baryons. In the meson sector, Eichten *et al.* explored the influence of the open-charm channels on the charmonium properties using the Cornell coupled-channel model [1] to assess departures from the single-channel potential-model expectations.

In this work we present the latest applications of the UQM to study the flavor asymmetry and strangeness of the proton, in which the effects of the sea quarks were introduced into the CQM in a systematic way and the wave functions were given explicitly. Finally, the UQM is applied to describe meson observables and the spectroscopy of the charmonium and bottomonium.

2. The Unquenched Quark Model

In the UQM for baryons [19, 21–23] and mesons [24–27], the hadron wave function is made up of a zeroth order qqq ($q\bar{q}$) configuration plus a sum over the possible higher Fock components, due to the creation of 3P_0 $q\bar{q}$ pairs. Thus, we have

$$|\psi_A\rangle = \mathcal{N} \left[|A\rangle + \sum_{BC\ell J} \int d\vec{K} k^2 dk |BC\ell J; \vec{K}k\rangle \frac{\langle BC\ell J; \vec{K}k | T^\dagger | A\rangle}{E_a - E_b - E_c} \right], \quad (1)$$

where T^\dagger stands for the 3P_0 quark-antiquark pair-creation operator [24–27], A is the baryon/meson, B and C represent the intermediate state hadrons. E_a , E_b and E_c are the corresponding energies, k and ℓ the relative radial momentum and orbital angular momentum between B and C and $\vec{J} = \vec{J}_b + \vec{J}_c + \vec{\ell}$ is the total angular momentum. It is worthwhile noting that in Refs. [24–28], the constant pair-creation strength in the operator (1) was substituted with an effective one, to suppress unphysical heavy quark pair-creation.

The introduction of continuum effects in the CQM can thus be essential to study observables that only depend on $q\bar{q}$ sea pairs, like the strangeness content of the nucleon electromagnetic form factors [18, 19] or the flavor asymmetry of the nucleon sea [21]. The continuum effects can give important corrections to baryon/meson observables, like the self-energy corrections to meson masses [24–27] or the importance of the orbital angular momentum in the spin of the proton [22].

3. Flavour content in the proton

The evidence for the flavor asymmetry of the proton sea was found by NMC at CERN [29]. The flavor asymmetry in the proton is related to the Gottfried integral for the difference of the proton and neutron electromagnetic structure functions

$$S_G = \int_0^1 dx \frac{F_2^p(x) - F_2^n(x)}{x} = \frac{1}{3} - \frac{2}{3} \int_0^1 dx [\bar{d}(x) - \bar{u}(x)] . \quad (2)$$

If one takes a flavor symmetric sea, one obtains the Gottfried sum rule $S_G = 1/3$, but the final NMC value is 0.2281 ± 0.0065 at $Q^2 = 4$ (GeV/c) 2 for the Gottfried integral over the range $0.004 \leq x \leq 0.8$ [29], which implies a flavor asymmetric sea. The Gottfried sum rule has been confirmed by other experimental collaborations [30, 31]. Theoretically, it was shown in Ref. [32], that the coupling of the nucleon to the pion cloud provides a natural mechanism to produce a flavor asymmetry. In the UQM, the flavor asymmetry can be calculated from the difference of the probability to find \bar{d} and \bar{u} sea quarks in the proton. Our result is shown in Fig. 1.

In a second stage, we calculated the strangeness content of the nucleon, see ref. [19]. In the UQM the strange magnetic moment of the proton is defined as the expectation value of the operator

$$\vec{\mu}_s = \sum_i \mu_{i,s} \left[2\vec{s}(q_i) + \vec{l}(q_i) - 2\vec{s}(\bar{q}_i) - \vec{l}(\bar{q}_i) \right] \quad (3)$$

on the proton state of Eq. (1), which represents the contribution of the strange quarks to the magnetic moment of the proton; $\mu_{i,s}$ is the magnetic moment of the quark i times a projector on strangeness and the strange quark magnetic moment is set as in Ref. [23]. Our result is $\vec{\mu}_s = 0.0006\mu_N$ (see Fig. 2).

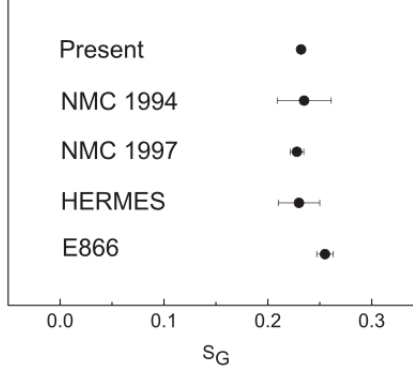


Fig. 1. Comparison the value of Gottfried sum rule calculated within UQM with the experimental data from NMC 1994, NMC 1997, HERMES, and E866. Figure taken from Ref. [23]; APS copyright.

Similarly, the strange radius of the proton is defined as the expectation value of the operator

$$R_s^2 = \sum_{i=1}^5 e_{i,s} \left(\vec{r}_i - \vec{R}_{\text{cm}} \right)^2 \quad (4)$$

on the proton state of Eq. (1), where $e_{i,s}$ is the electric charge of the quark i times a projector on strangeness, \vec{r}_i and \vec{R}_{cm} are the coordinates of the quark i and of the intermediate state center of mass, respectively. The expectation value of R_s^2 on the proton is equal to -0.004fm^2 . In Fig. 3 our result is compared with the experimental data.

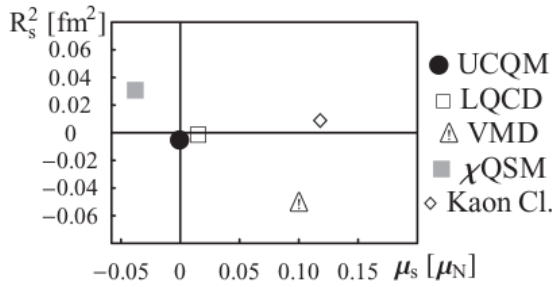


Fig. 2. The UQM results for the strange magnetic moment and radius of the proton. Figure taken from Ref. [19]; APS copyright.

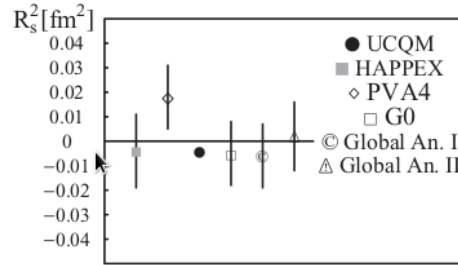


Fig. 3. Comparison between our resulting value for the strange radius of the proton in the UQM. Figure taken from Ref. [19]; APS copyright.

4. Self-energy corrections in the UQM

The method was used by some of us to compute the charmonium ($c\bar{c}$) and bottomonium ($b\bar{b}$) spectra with self-energy corrections, due to continuum coupling effects [24–27]. In the UQM, the physical mass of a meson,

$$M_a = E_a + \Sigma(E_a) , \quad (5)$$

is given by the sum of two terms: a bare energy, E_a , calculated within a potential model [3], and a self energy correction,

$$\Sigma(E_a) = \sum_{BC\ell J} \int_0^\infty k^2 dk \frac{|M_{A \rightarrow BC}(k)|^2}{E_a - E_b - E_c}, \quad (6)$$

computed within the UQM formalism.

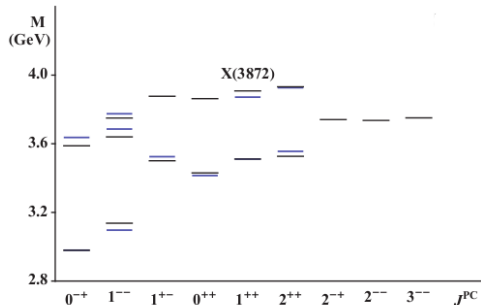


Fig. 4. Charmonium spectrum with self energies corrections. Black lines are theoretical predictions and blue lines are experimental data available. Figure taken from Ref. [25]; APS copyright.

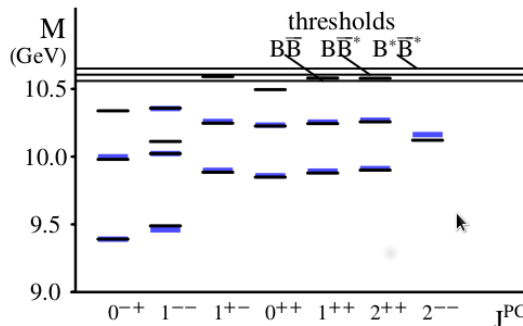


Fig. 5. Bottomonium spectrum with self energies corrections. Black lines are theoretical predictions and blue lines are experimental data available. Figure taken from Ref. [26]; APS copyright.

Our results for the self energies corrections of charmonia [25,27] and bottomonia [24,26,27] spectrums, are shown in figures 4 and 5.

5. Discussion and conclusion

The asymmetry and "strangeness" observables in the proton can only be understood when continuum components in the wave function are included. Our results, as shown in Figures 1, 2 and 3, are in agreement with the experimental data.

The self energies corrections of charmonium and bottomonium spectra, see figures 4 and 5, show that the pair-creation effects on the spectrum of heavy mesons are quite small. Specifically for charmonium and bottomonium states, they are of the order of 2 – 6% and 1%, respectively. The relative mass shifts, i.e. the difference between the self energies of two meson states, are in the order of a few tens of MeV.

In our framework the $X(3872)$ can be interpreted as a $c\bar{c}$ core [the $\chi_{c1}(2^3P_1)$], plus higher Fock components due to the coupling to the meson-meson continuum. In Ref. [27], we obtained that the probability to find the $X(3872)$ in its core or continuum components is approximately 45% and 55%, respectively.

In conclusion, the flavor asymmetry in the proton is well described by the UQM. The "strangeness" observables of the proton are found to be negligible and our results compatible with the latest experimental data and recent lattice calculations. Finally, our self energies corrections for charmonium and bottomonium spectra are found to be significant.

Acknowledgments

This work is supported in part by PAPIIT-DGAPA, Mexico (grant IN107314) and INFN sezione di Genova .

References

- [1] E. Eichten, K. Gottfried, T. Kinoshita, J. B. Kogut, K. D. Lane and T. -M. Yan: *Phys. Rev. Lett.* **34** (1975) 369; E. Eichten, K. Gottfried, T. Kinoshita, K. D. Lane and T. -M. Yan: *Phys. Rev. D* **17** (1978) 3090; *Phys. Rev. D* **21** (1980) 203.
- [2] N. Isgur and G. Karl: *Phys. Rev. D* **18** (1978) 4187; *Phys. Rev. D* **19** (1979) 2653 [Erratum-ibid. **23** (1981) 817]; *Phys. Rev. D* **20** (1979) 1191.
- [3] S. Godfrey and N. Isgur: *Phys. Rev. D* **32** (1985) 189.
- [4] S. Capstick and N. Isgur: *Phys. Rev. D* **34** (1986) 2809.
- [5] M. Ferraris, M. M. Giannini, M. Pizzo, E. Santopinto and L. Tiator: *Phys. Lett. B* **364** (1995) 231; E. Santopinto, F. Iachello and M. M. Giannini: *Eur. Phys. J. A* **1** (1998) 307; E. Santopinto and G. Giannini: *Phys. Rev. C* **86** (2012) 065202; M. M. Giannini, E. Santopinto: *Chin. J. Phys.* **53** (2015) 020301; M. Aiello, *et al.*: *Phys. Lett. B* (1996) 387, 215; Aiello *et al.* *J. of Phys. G* **24** (1988) 753; R. Bijker, F. Iachello, E. Santopinto: *J. of Phys. A* **31** (1988) 9041; M. De Sanctis *et al.*: *Phys. Rev. C* **6** (2007) 062201; M. M. Giannini *et al.*: *Eur. Phys. J. A* **12** (2001) 447; De Sanctis *et al.*: *Phys. Rev. C* **62** (2000) 025208; M. De Sanctis *et al.*: *Eur. Phys. J. A* **1**, (1998) 187; De Sanctis, M. M. Giannini, E. Santopinto *et al.*: *Nucl. Phys. A* **755** (2005) 294; De Sanctis, M. M. Giannini, E. Santopinto *et al.*: *Eur. Phys. J. A* **19** (2005) 81; E. Santopinto, A. Vassallo, M. M. Giannini *et al.*: *Phys. Rev. C* **82** (2010) 065204.
- [6] L. Y. Glozman, D. O. Riska: *Phys. Rept.* **268** (1996) 263; L. Y. Glozman, W. Plessas, K. Varga, R. F. Wagenbrunn: *Phys. Rev. D* **58** (1998) 094030.
- [7] U. Loring, B. C. Metsch and H. R. Petry: *Eur. Phys. J. A* **10** (2001) 395.
- [8] E. Santopinto: *Phys. Rev. C* **72** (2005) 022201; J. Ferretti, A. Vassallo and E. Santopinto: *Phys. Rev. C* **83** (2011) 065204; M. De Sanctis, J. Ferretti, E. Santopinto and A. Vassallo: arXiv:1410.0590; M. De Sanctis, J. Ferretti, E. Santopinto: *Phys. Rev. C* **84** (2011) 055201; E. Santopinto; J. Ferretti: *Phys. Rev. C* **92**, 025202(2015).
- [9] G. Galatà and E. Santopinto: *Phys. Rev. C* **86** (2012) 045202.
- [10] R. Bijker, F. Iachello and A. Leviatan: *Ann. Phys. (N.Y.)* **236** (1994) 69; *Phys. Rev. C* **54** (1996) 1935; *Phys. Rev. D* **55** (1997) 2862; *Ann. Phys. (N.Y.)* **284** (2000) 89.
- [11] E. van Beveren, C. Dullemond and G. Rupp: *Phys. Rev. D* **21** (1980) 772 [Erratum-ibid. **D 22** (1980) 787].
- [12] E. van Beveren, T. A. Rijken, K. Metzger, C. Dullemond, G. Rupp and J. E. Ribeiro: *Z. Phys. C* **30** (1986) 615.
- [13] S. Ono and N. A. Törnqvist: *Z. Phys. C* **23** (1984) 59; K. Heikkilä, S. Ono and N. A. Törnqvist: *Phys. Rev. D* **29** (1984) 110 [Erratum-ibid. **29** (1984) 2136]; S. Ono, A. I. Sanda and N. A. Törnqvist: *Phys. Rev. D* **34** (1986) 186.
- [14] N. A. Törnqvist and P. Zenczykowski: *Phys. Rev. D* **29** (1984) 2139; *Z. Phys. C* **30** (1986) 83; P. Zenczykowski: *Annals Phys.* **169** (1986) 453.
- [15] N. A. Törnqvist: *Z. Phys. C* **68** (1995) 647.
- [16] M. Boglione and M. R. Pennington: *Phys. Rev. D* **65** (2002) 114010.
- [17] P. Geiger and N. Isgur: *Phys. Rev. D* **41** (1990) 1595.
- [18] P. Geiger and N. Isgur: *Phys. Rev. D* **55** (1997) 299.
- [19] R. Bijker, J. Ferretti and E. Santopinto: *Phys. Rev. C* **85** (2012) 035204.
- [20] S. Capstick and D. Morel: [nucl-th/0204014].
- [21] E. Santopinto and R. Bijker: *Phys. Rev. C* **82** (2010) 062202.
- [22] E. Santopinto and R. Bijker: *Few Body Syst.* **44** (2008) 95.
- [23] R. Bijker and E. Santopinto: *Phys. Rev. C* **80** (2009) 065210.
- [24] J. Ferretti, G. Galatà, E. Santopinto and A. Vassallo: *Phys. Rev. C* **86** (2012) 015204.
- [25] J. Ferretti, G. Galatà and E. Santopinto: *Phys. Rev. C* **88** (2013) 015207.
- [26] J. Ferretti, and E. Santopinto: *Phys. Rev. D* **90** (2014) 094022.
- [27] J. Ferretti, G. Galatà and E. Santopinto: *Phys. Rev. D* **90** (2014) 054010.
- [28] Y. S. Kalashnikova: *Phys. Rev. D* **72** (2005) 034010.
- [29] P. Amaudruz, *et al.*: *Phys. Rev. Lett.* **66** (1991) 2712; M. Arneodo *et al.*: *Nucl. Phys. B* **487** (1997) 3.
- [30] K. Ackerstaff *et al.*: *Phys. Rev. Lett.* **81** (1988) 5519.

- [31] R. S. Towell *et al.*: *Phys. Rev. D* **64** (2001) 052002.
- [32] A. W. Thomas: *Phys. Lett. B* **126** (1983) 97.